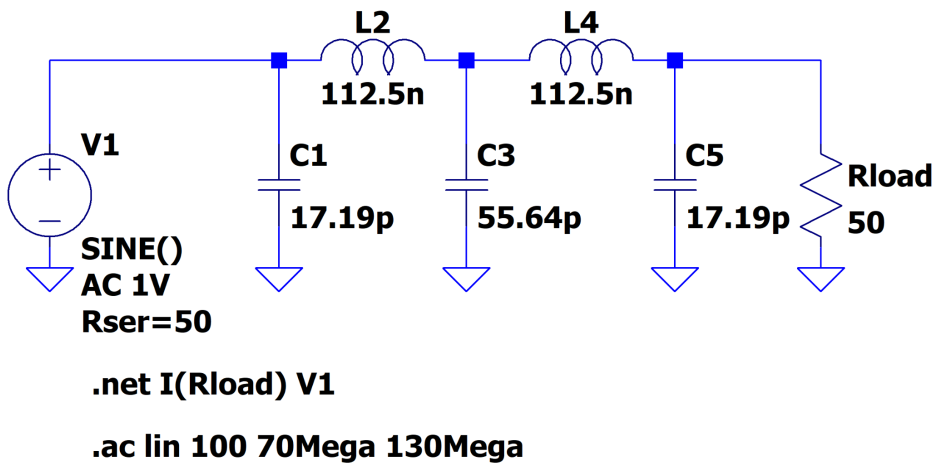
RF Design Project 1 - Shreya Jampana

1. The following table

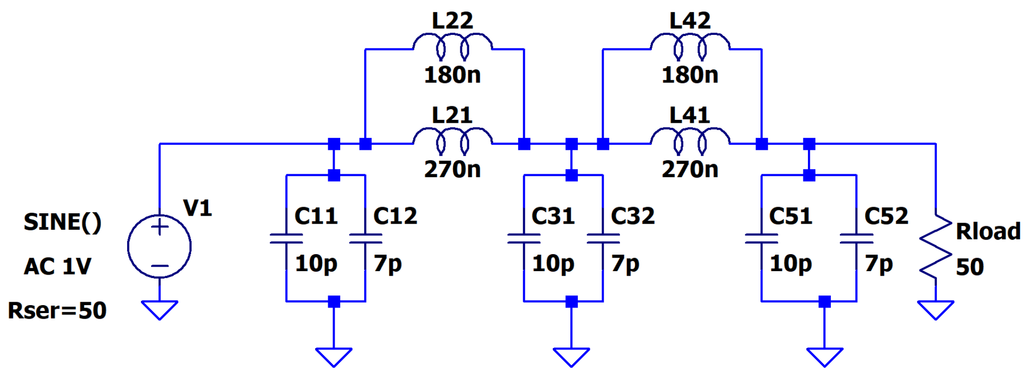
Parameter	Analytical	Simulated w/ ideal components	Simulated w/ real components	Measured
Filter type (Butterworth, Chebyshev I, etc.)	Butterworth	NA	NA	NA
Filter order	5	NA	NA	NA
Pass Band Edge (defined as exceeding 1dB ripple)	100 MHz	100.05 MHz	110.6 MHz	104 MHz
Stop Band Start (defined @20dB of rejection)	200 MHz	180.99 MHz	214 MHz	190 MHz
Insertion Loss	0 dB	0 dB	0 dB	0.67 dB
In-Band Ripple	1 dB	1 dB	1 dB (calculated using a 0.5 dB ripple)	1 dB

2. Pictures and schematics:

Schematic with Ideal Components

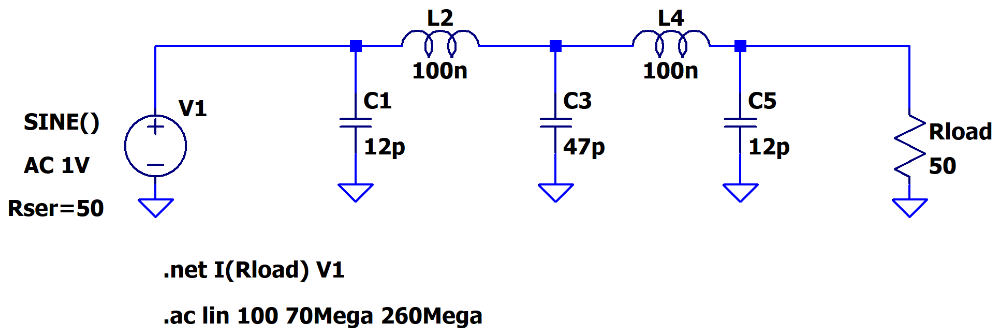


Schematic with Real Components (before accounting for parasitics)

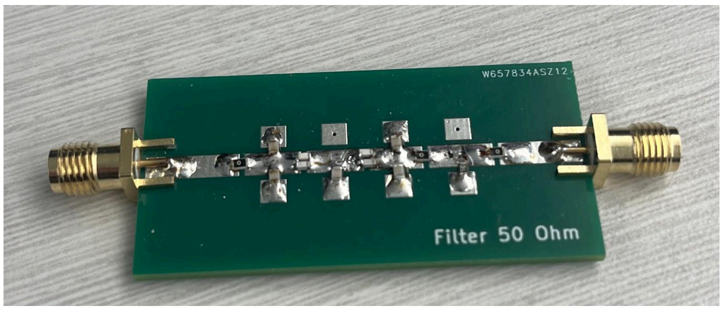


Schematic with Real Components (after accounting for parasitics)

The parasitics we accounted for are not shown on the schematic below, because we did not calculate and include them analytically. Instead, we accounted for the effects of board parasitics by scaling the components appropriately to negate the effects of the parasitics.

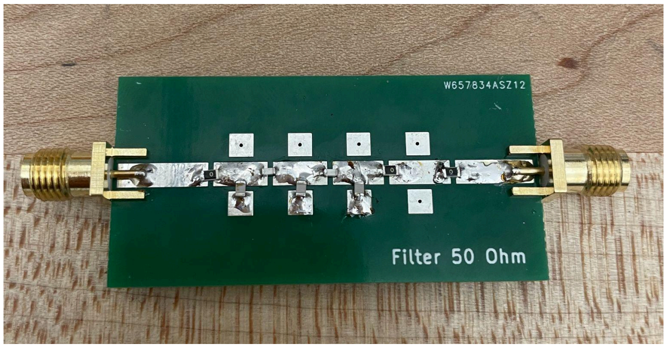


Picture of Assembled Circuit (before accounting for parasitics)



Picture of Assembled Circuit (after accounting for parasitics)

Note: We decreased the number of components and also removed the 51 ohm resistor in the shunt because we used the 50 ohm shunt component provided by Port 2.



3.

*Used filter design table from "Filter Design with Tables" file posted on canvas

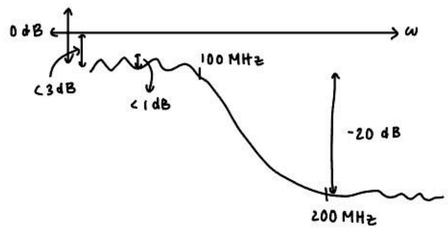
Ideal Calculations

3. Requirements:

- pass band: 100 MHz
- stop band: 200 MHz
- insertion loss < 3 dB
- in band ripple < 1 dB
- 20 dB rejection in stop band
- $Z_S = Z_L = 50\,\Omega$
- low pass

Translating Requirements:

Low pass:



Considering options

Butterworth
- flat pass band
- rolls off at -20n dB/dec
- common/easy

Chebyshev I
- ripple in pass band X
- faster roll off

Chebyshev II
- fast roll off
- stop band ripple

choosing butterworth over chebyshev due to simplicity

Butterworth

Finding ϵ from allowable passband deviation, which for us is 1 dB:

$$\epsilon = \sqrt{10^{0.1 \delta} - 1} = \sqrt{10^{(0.1)(1)} - 1} = 0.509$$

⇒ ensuring in-band ripple is achievable by design

Finding filter order using the following equation:

$$n = \frac{\ln\left(\frac{A_s}{\epsilon}\right)}{\ln\left(\frac{\omega}{\omega_c}\right)}$$

A_s = 20 dB (attenuation in dB) so 10 in linear space

$10\log(|H(j\omega)|^2) = 20$

$\log(H(j\omega)) = 1$

$|H(j\omega)| = 10$

ϵ = 0.509 (calculated above)

ω = 200 MHz (where attenuation is desired)

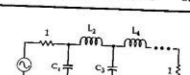
ω_c = 100 MHz (cutoff frequency)

$$n = \frac{\ln\left(\frac{10}{0.509}\right)}{\ln\left(\frac{200}{100}\right)} \approx 4.30$$

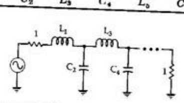
⇒ ensuring stop band rejection is achievable by design

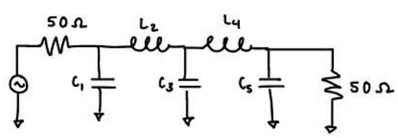
∴ choosing 5th order b/c rounding up

Butterworth Filter Table



n	C_1	L_2	C_3	L_4	C_5	L_6	C_7
2	1.414	1.414					
3	1.000	2.000	1.000				
4	0.765	1.848	1.848	0.765			
5	0.618	1.618	2.000	1.618	0.618		
6	0.518	1.414	1.932	1.932	1.414	0.518	
7	0.445	1.247	1.802	2.000	1.802	1.247	0.445
n	L_1	C_2	L_3	C_4	L_5	C_6	L_7





C_1 = 0.61

L_2 = 1.618

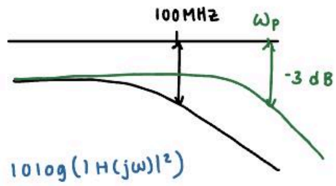
C_3 = 2.000

L_4 = 1.618

C_5 = 0.618

need to unnormalize these values using ω_p

We need the pass band edge, the point where the TF reaches -1 dB, to be 100 MHz. The corner frequency is when the TF reaches -3 dB. In order for the pass band edge to be -1 dB, the corner frequency, ω_p, needs to be higher. Solving for ω_p:



Trying to find ω_p so rolloff starts later and allows us to keep 100 MHz at -1 dB

$$-1 \text{ dB} = 10\log(|H(j\omega)|^2)$$

$$|H(j\omega)|^2 = \frac{1}{1+\left(\frac{\omega}{\omega_p}\right)^{2n}}$$

dropping ε from equation b/c we're defining ω_p at -3 dB (using same transfer function as filter table assumes)

$$10^{-0.1} = \frac{1}{1+\left(\frac{100}{\omega_p}\right)^{10}}$$

$$\omega_p \approx 114.468 \text{ MHz}$$

Now, un-normalizing values from filter table using ω_p:

$$\omega_p L = z_0 (1 \text{ rad/sec}) L_{normalized}$$

$$L = \frac{R L_{norm.}}{\omega_p}$$

$$L = \frac{50 L_{norm}}{2\pi(114.5 \times 10^6)}$$

$$\frac{1}{\omega_p C} = \frac{z_0}{(1 \text{ rad/s}) C_{normalized}}$$

$$C = \frac{C_{norm}}{R\,\omega_p}$$

$$C = \frac{C_{norm}}{(50)(2\pi)(114.5 \times 10^6)}$$

Using these to convert normalized values from table:

$C_1 = 0.618$
$L_2 = 1.618$
$C_3 = 2.000$
$L_4 = 1.618$
$C_5 = 0.618$

$\Longrightarrow$

$C_1 = 1.718 \times 10^{-11}$ F ≈ 17.18 pF
$L_2 = 1.125 \times 10^{-7}$ H ≈ 112.5 nH
$C_3 = 5.56 \times 10^{-11}$ F ≈ 55.6 pF
$L_4 = 1.125 \times 10^{-7}$ H ≈ 112.5 nH
$C_5 = 1.718 \times 10^{-11}$ F ≈ 17.18 pF

Stop Band Rejection:

$$|H(j\omega)|^2 = \frac{1}{1+\varepsilon^2(\omega_s/\omega_p)^{2n}}$$

$$10\log(|H(j\omega)|^2) = -20 \text{ dB}$$

$$\frac{1}{1+(0.509)^2\left(\frac{\omega_s}{100}\right)^{10}} = 10^{-2}$$

$\omega_s = 181.226$ $\Longrightarrow$ stop band rejection is achievable

Real Calculations (after accounting for parasitics):

Butterworth

Choosing new allowable deviation to be 0.5 dB:

$$\epsilon = \sqrt{10^{0.1(0.5)} - 1} = 0.349 \Rightarrow$$ ensuring in-band ripple is achievable by design

Finding filter order using the following equation:

$10\log(|H(j\omega)|^2) = 20$
$\log(H(j\omega)) = 1$
$|H(j\omega)| = 10$

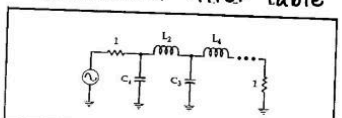
$$n = \frac{\ln\left(\frac{A_s}{\epsilon}\right)}{\ln\left(\frac{\omega}{\omega_c}\right)}$$

$A_s = 20\,dB$ (attenuation in dB) so 10 in linear space
$\epsilon = 0.349$ (calculated above)
$\omega = 200\,MHz$ (where attenuation is desired)
$\omega_c = 100\,MHz$ (cutoff frequency)

$$n = \frac{\ln\left(\frac{10}{0.349}\right)}{\ln\left(\frac{200}{100}\right)} \approx 4.84 \Rightarrow$$ ensuring stop band rejection is achievable by design

still a 5th order circuit

Butterworth Filter Table



n	C_1	L_2	C_3	L_4	C_5	L_6	C_7
2	1.414	1.414					
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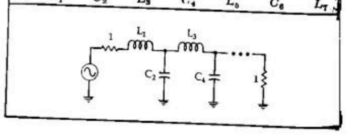
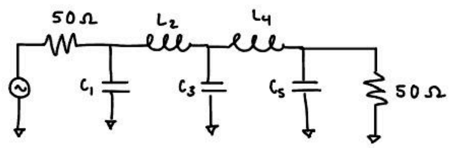
n	L_1	C_2	L_3	C_4	L_5	C_6	L_7





$C_1 = 0.61$
$L_2 = 1.618$
$C_3 = 2.000$
$L_4 = 1.618$
$C_5 = 0.618$

need to unnormalize these values using ω_p

Calculating new ω_p using new allowable deviation of 0.5 dB:

$$|H(j\omega)|^2 = \frac{1}{1 + \left(\frac{\omega}{\omega_p}\right)^{2n}}$$

$-0.5\,dB = 10\log(|H(j\omega)|^2)$

$$10^{-0.05} = \frac{1}{1 + \left(\frac{100}{\omega_p}\right)^{10}}$$

$$\omega_p \approx 123.41\,MHz$$

Now, un-normalizing values from filter table using ω_p:

$$\omega_p L = Z_0(1\,rad/sec)\,L_{normalized}$$

$$L = \frac{R\,L_{norm.}}{\omega_p}$$

$$L = \frac{50\,L_{norm}}{2\pi(123.41 \times 10^6)}$$

$$\frac{1}{\omega_p C} = \frac{Z_0}{(1\,rad/s)\,C_{normalized}}$$

$$C = \frac{C_{norm}}{R\,\omega_p}$$

$$C = \frac{C_{norm}}{(50)(2\pi)(123.41 \times 10^6)}$$

using these to convert normalized values from table:

$C_1 = 0.618$
$L_2 = 1.618$
$C_3 = 2.000$
$L_4 = 1.618$
$C_5 = 0.618$

$\Longrightarrow$

$C_1 = 1.718 \times 10^{-11}$ F ≈ 15.95 pF
$L_2 = 1.125 \times 10^{-7}$ H ≈ 104.38 nH
$C_3 = 5.56 \times 10^{-11}$ F ≈ 51.61 pF
$L_4 = 1.125 \times 10^{-7}$ H ≈ 104.38 nH
$C_5 = 1.718 \times 10^{-11}$ F ≈ 15.95 pF

stop Band Rejection:

$$|H(j\omega)|^2 = \frac{1}{1+\varepsilon^2(\omega_s/\omega_p)^{2n}}$$

$$10\log\left(|H(j\omega)|^2\right) = -20 \text{ dB}$$

$$\frac{1}{1+(0.349)^2\left(\frac{\omega_s}{100}\right)^{10}} = 10^{-2}$$

$\omega_s = 195.433$ $\Longrightarrow$ stop band rejection is achievable

Explaining how specs are met: Both sets of calculations, for the ideal and real cases, show that the in-band ripple is achievable by the design. In both cases, we chose the allowable in-band ripple value (1 dB in the real, and 0.5 dB in the real), which is how we derived our epsilon value. The epsilon value was then used to derive the order of the circuit. Both of these were then used to get wp for this circuit. The calculations for stop band reject frequency is also shown above, and in both cases, we got a value under 200 MHz. Since this means that we are below 20dB at 200 MHz, our stop band rejection spec was also met. Therefore, our calculations above show that the in-band ripple and stop-band rejection specs are met.

Other comments: I included two sets of calculations (one for the ideal, and one for the real after accounting for parasitics), because they have different components. When we initially assembled the circuit (as seen in “Picture of Assembled Circuit (before accounting for parasitics)”), we used multiple inductors and capacitors in parallel to get close to the ideal components. The exact components we used are seen in the ”Schematic with Real Components (before accounting for parasitics). With this setup however, we observed a deviation or in-band ripple of around 2dB at the desired pass band edge of 100 MHz. To fix this to meet the specs, we recalculated our component values for a new allowable pass band deviation of 0.5 dB, which is shown in the second set of calculations above. We also hypothesized that board parasitics could be behind our design not meeting the specs, as they seemed to cause our magnitude plot to shift to the left. We simulated our new design, and noted that reducing C_1 and C_5 causes the graph to shift left, and reducing L_2, L_4, and C_3 causes the graph to shift right. So, we decided that when choosing the available capacitors and inductors, we should round down to shift the graph to the right to counteract the effect of board parasitics. This led us to choosing $C_1 = C_5 = 12$ pF, $C_3 = 47$ pF, and $L_2 = L_4 = 100$ nH. Although the C_3 value of 47pF is much lower than our calculated value of 52pF, we decided to try it out with this value first and add another capacitor in parallel to increase the capacitance (and shift the graph a little to the left) based on initial measurements.

Power delivered to a 50 ohm load:

Insertion loss (S21) at 50 MHz:

4.97E+07	-5.26E-01
5.01E+07	-5.22E-01

Calculation showing power delivered to load:

power delivered to load: $P_\ell = \dfrac{|V_s|^2}{8Z_0} \cdot |S_{21}|^2$

$Z_S = Z_L = Z_0 = 50$

1 Vpp $\longrightarrow$ $V_{rms} = \dfrac{1}{2\sqrt{2}} = 0.353$

$-0.522 \text{ dB} = 10\log\left(|S_{21}|^2\right)$

$|S_{21}|^2 = 10^{-0.522/10} = 0.8867$ converting from dB

$P_\ell = \dfrac{(0.353)^2}{8(50)} \cdot |S_{21}|^2$

$P_\ell = (3.115 \times 10^{-4})|S_{21}|^2$ insertion loss

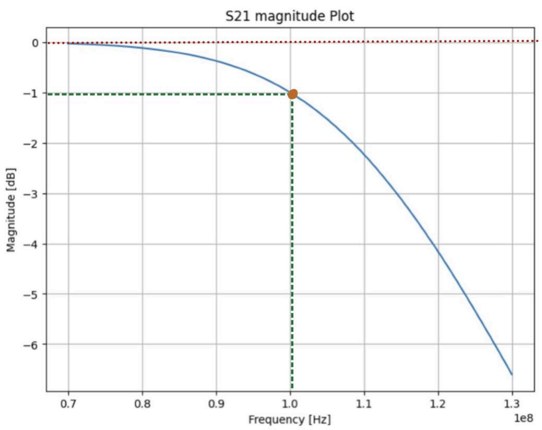
$P_\ell = (3.115 \times 10^{-4})(0.8867) = 2.76 \times 10^{-4}$ W

$P_\ell = 0.276$ mW

4. Magnitude of S21 in your pass band for all four designs

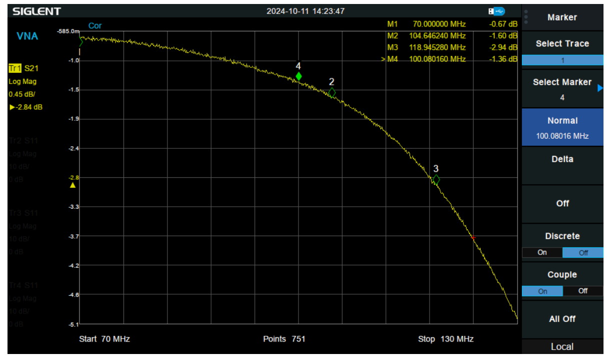
Cursors on simulation show the markers, but I also wrote it down to make it easier to read.

Analytical

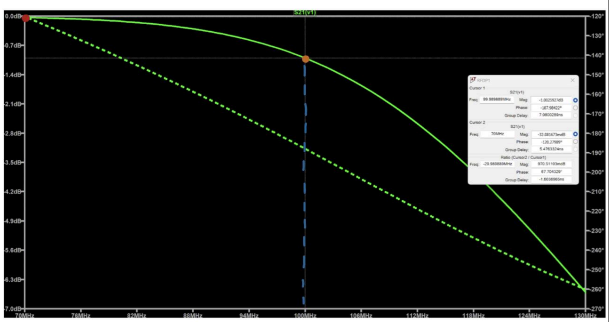


maximum value in pass band: 0 dB at 70 MHz
pass band edge: -1 dB at 100 MHz
1 dB ripple also at 100 MHz

Measured

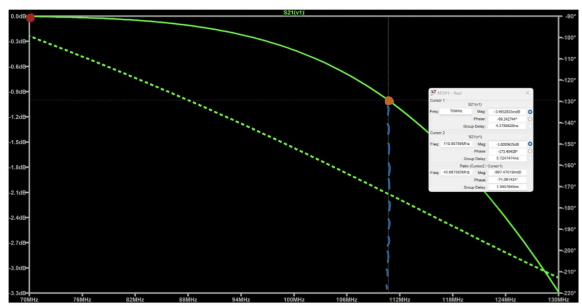


Simulated Ideal



maximum value in pass band - 0 dB at 70 MHz
minimum ripple value - 1 dB at 100 MHz
same as pass band edge

Simulated Real

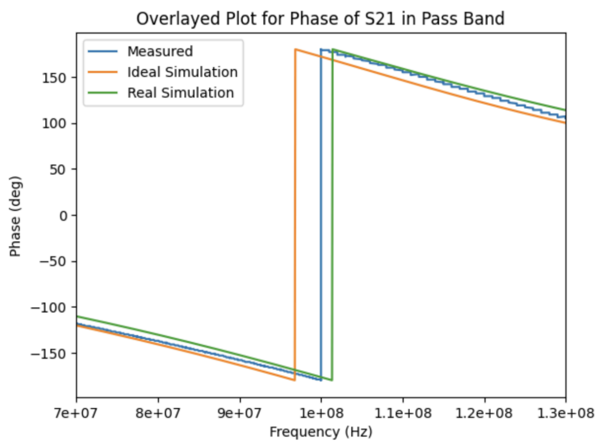


maximum value in pass band - 0 dB at 70 MHz
minimum ripple value - 1 dB at 110 MHz
same as pass band edge

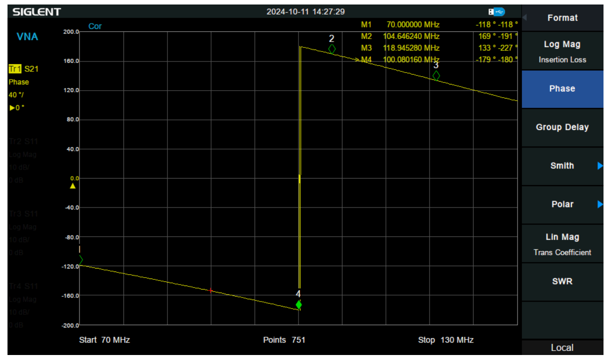
5. Phase of S21 in your pass band for three designs: the ideal simulation, the real simulation and the measured design.

Markers are on each individual plot because it's easier to read. Cursors on simulation show the markers, but I also wrote it down to make it easier to read.

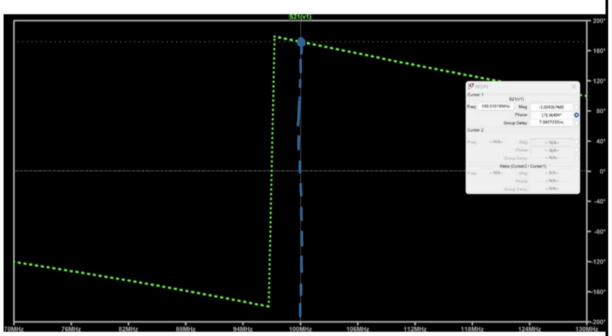
Overlaid Phase Plot



Measured

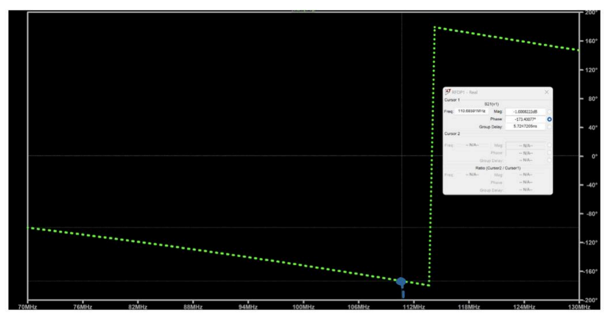


Simulated Ideal



pass band edge: phase = 171.96° at 100 MHz

Simulated Real

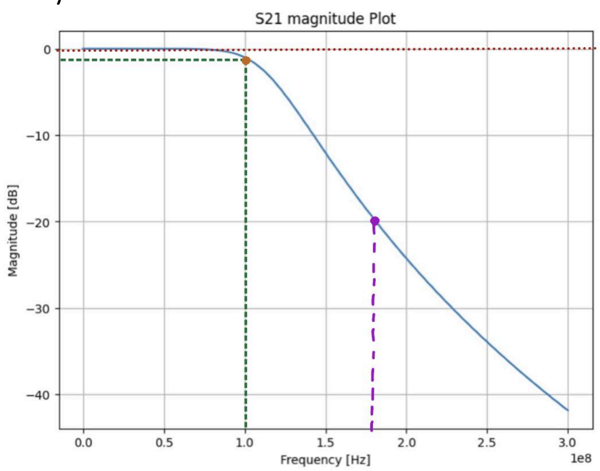


pass band edge: phase = -173.4° at 100 MHz

6. Magnitude of S21 from DC to your stop band for all four designs

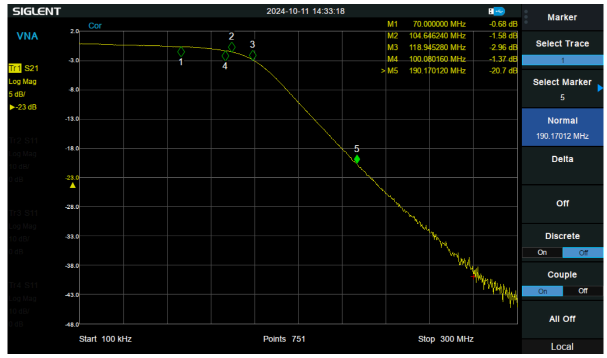
Cursors on simulation show the markers, but I also wrote it down to make it easier to read.

Analytical

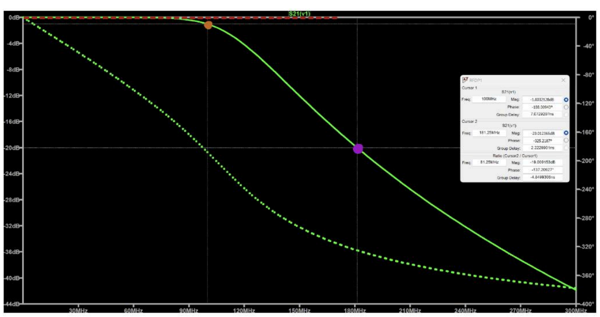


insertion loss: 0 dB at 0 MHz
pass band edge: -1 dB at 100 MHz
stop band edge: -20 dB at 180 MHz

Measured

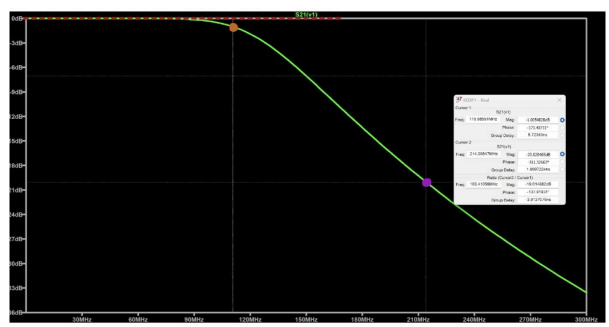


Simulated Ideal



insertion loss: 0 dB at 0 MHz
pass band edge: -1 dB at 100 MHz
stop band edge: -20 dB at 181 MHz

Simulated Real

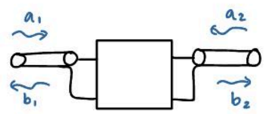


insertion loss: 0 dB at 0 MHz
pass band edge: -1 dB at 110.68 MHz
stop band edge: -20 dB at 214 MHz

7. Magnitude of S11 from DC to your stop band for all four designs, including derivation.

Cursors on simulation show the markers, but I also wrote it down to make it easier to read.

Derivation of S11 from S21 magnitude and power conservation



$S_{21} = \frac{b_2}{a_1}$ $\qquad$ $S_{11} = \frac{b_1}{a_1}$ (deriving this)

Applying power conservation: power in = power out

$$\frac{1}{2}|a_1|^2 = \frac{1}{2}|b_1|^2 + \frac{1}{2}|b_2|^2$$

due to being terminated at the load, assume no a_2 (no reflection back)

$$|a_1|^2 = |b_1|^2 + |b_2|^2$$

$$\frac{|a_1|^2 - |b_2|^2}{|a_1|^2} = \frac{|b_1|^2}{|a_1|^2}$$

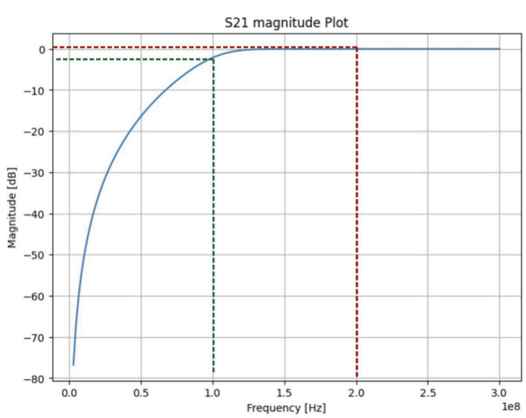
$$1 - \frac{|b_2|^2}{|a_1|^2} = \frac{|b_1|^2}{|a_1|^2}$$

$$\sqrt{1 - \left(\left|\frac{b_2}{a_1}\right|\right)^2} = \sqrt{\left|\frac{b_1}{a_1}\right|^2}$$

$$\sqrt{1 - |S_{21}|^2} = \sqrt{|S_{11}|^2}$$

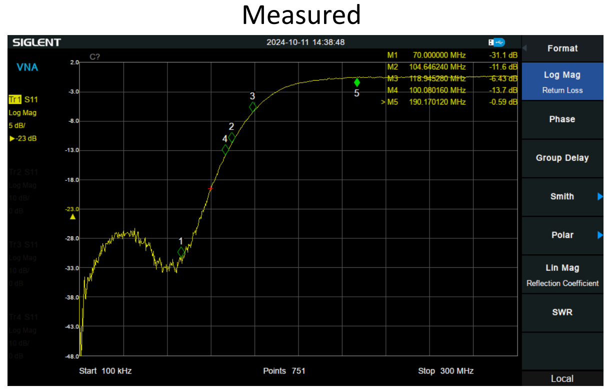
$$\boxed{|S_{11}| = \sqrt{1 - |S_{21}|^2}}$$

<table>
<tr><th>Analytical</th><th>Measured</th></tr>
<tr><td>



pass band edge: -2 dB at 100 MHz
stop band edge: 0 dB at 200 MHz

</td><td>



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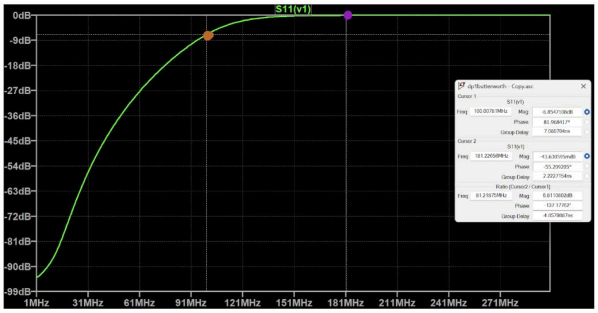
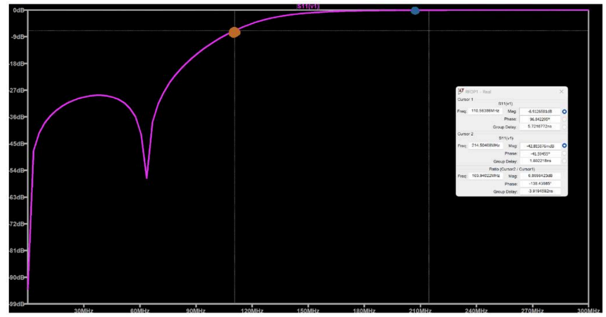
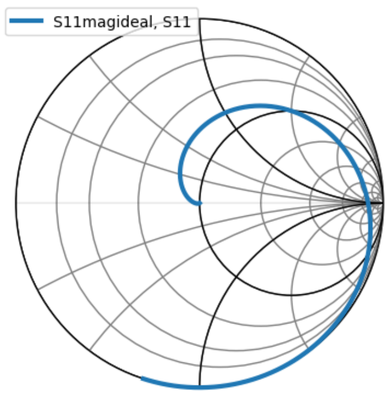
</table>

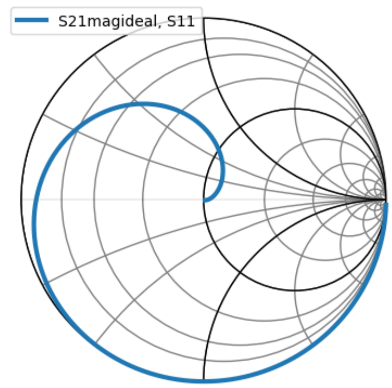
Simulated Ideal	Simulated Real
	
pass band edge: -6.8 dB at 100 MHz stop band edge: 0 dB at 181.23 MHz	pass band edge: -6.9 dB at 100 MHz stop band edge: 0 dB at 200 MHz

8. Smith Charts for S11 and S21 from DC to your stop band for three designs: the ideal simulation, the real simulation and the measured results.

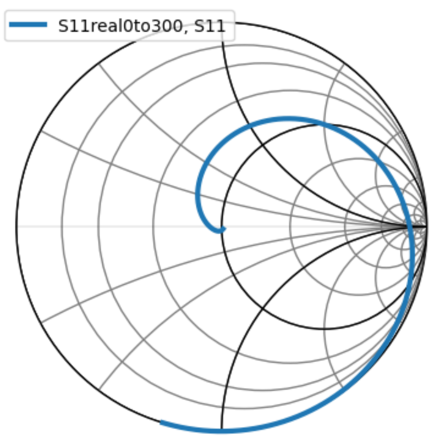
|S11| Ideal



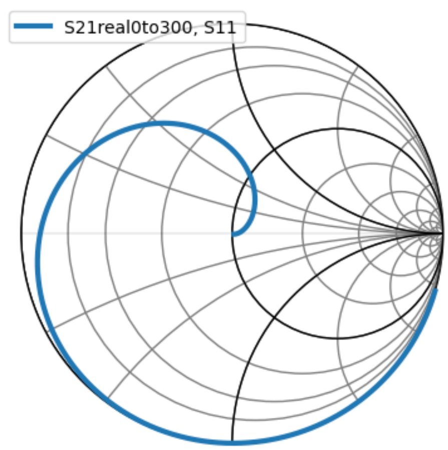
|S21| Ideal



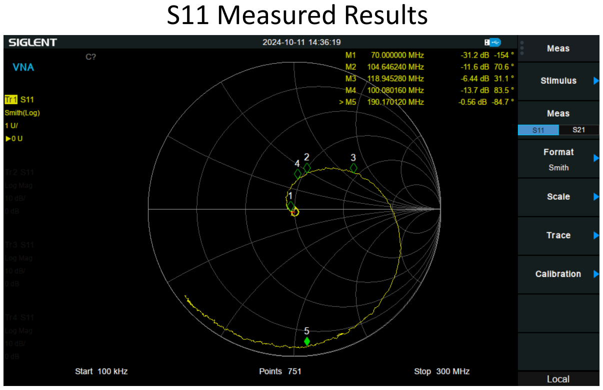
|S11| Real Simulated



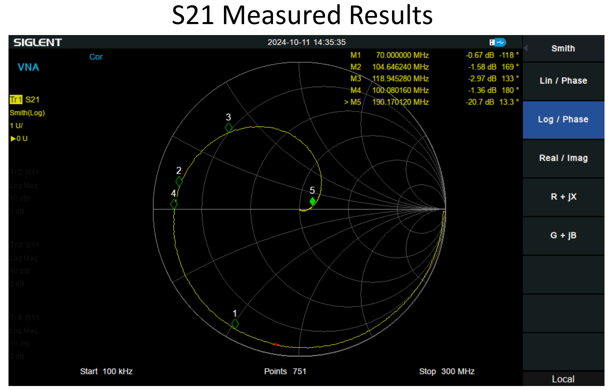
|S21| Real Simulated



S11 Measured Results



S21 Measured Results



9. Discussion of discrepancies between analytical, simulated and measured results. Quantitatively justify differences between them, including any modifications you made to your models to make your simulations match your measurements better (e.g.: board parasitics). Refer to prior figures in your report for supporting evidence in this discussion.

As expected, the analytical and ideal simulations matched pretty closely. Besides the S11 magnitude plot, all of the analytical and simulated ideals matched almost identically. For the S11 magnitude plot, although the general shape is the same, there was a difference in deviation at the 100 MHz point, with a magnitude of -2dB for the analytical and -6.8dB for the simulated. Since S11 was derived and calculated from S21, small differences in S21 from the analytical and ideal simulations could have carried over, causing this difference.

The board parasitics we were trying to account for included the PCB parasitic capacitance, and the parasitic capacitance and inductance from the vias. Because these are hard to measure, as described above, we accounted for these parasitics by rounding our component values down to shift the bode plot to the right (because we noticed that the parasitics shifted the plot to the left). Also to account for the parasitic effects, we did a brief re-design by choosing a new allowable ripple value of 0.5 dB instead of 1 dBTherefore, we did not really expect our ideal simulations to match our real ones after accounting for parasitics, which is why the simulated ideal and simulated real plots look a bit different, due to the difference in component values between the two.

All of the measured plots accounted for parasitics, because they were taken on the filter board on which we rounded the component values to shift the bode plot to the right. Because we changed component values to counteract the effects of parasitics, these measured plots match pretty closely to the analytical and ideal simulation plots. For example, looking at the magnitude of S21, the simulated and analytical plots had a pass-band edge for a 1dB ripple at 100 MHz, while the measured plots had that at 104 MHz. This slight difference could be attributed to the fact that the ideal simulation and analytical had 0dB of insertion loss, while the measured had an insertion loss of -0.67dB. Note that this means our measured data was within spec, because one of the requirements was that the insertion loss should be less than 3dB. Looking now at the stop band edge, the measured had a stop band edge (when it reached -20.67 dB, not -20dB, because the measured had insertion loss) at 190 MHz, while the analytical and real simulations had it at around 180 MHz. These values are close, and the slight differences could be attributed to the board parasitics, which although we tried to counteract, could not completely eliminate from our design. Note that the stop band edge of 190 MHz for our measure also indicates that the stop band edge spec was met by our design. Another difference we see between the measured and simulations is that the measured graph becomes a bit noisy at high frequencies. This can be attributed to the non-ideal behavior of the components at high frequencies. The measured, simulated, and analytical phase plots matched both in shape and value. The measured phase at the pass band edge (104 MHz) was around 169^{o}, which matched closely to the phase of around 171^{o} at the simulated ideal pass band edge (100 MHz). The S11 plots for the measured and real simulations match closely in shape. There is some deviation between the S11 analytical, ideal simulations, and measured, because they each have a magnitude of -2dB, -6.8 dB, and -11 dB at around 100 MHz. Again, I think this can be explained either with parasitics, or the fact that it was derived from S21.

The reason we displayed the magnitude and phase plots for the real simulations after accounting for parasitics was that we wanted to see if they matched hand calculations for the real components with a 0.5 dB restriction on in-band ripple. For the smith charts, in order to compare our measurements better, we kept with the components closest to our ideal measurements. The ideal, simulated, and measured match very closely for both S21 and S11, as seen visually in the table above. The only slight difference is that in the S11 Smith Chart, the measured chart shows a small loop at the center of the graph that curves a bit more than the simulation, which could be accounted for by parasitics. The rest of the behavior is the same and indicates the impedance match as expected.

10. One paragraph about one thing you learned about RF design doing this project.

I think I learned a lot about the general process behind RF filter design by doing this project. It helped me make practical use of all of the equations and abstractions we learn in class. The main thing I learned about RF, which is often hard to understand in a pure classroom setting, is how to account for parasitics in all of the components we use. I realized that it’s easy to draw the parasitic components from the board, but it’s really hard to hand-calculate and isolate these values in a lab setting. This project helped me figure out how I could change other parameters, such as the inductor and capacitor values in my ladder circuit, to counteract the effects of the parasitics even without knowing the numerical values of those parasitic components. In the process, I learned how important it is to constantly check between theory, simulations, and measurements to ensure all of the data I was seeing can be explained.